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Article

Design and Implementation of a Microcontroller-Based Boundary Marker Displacement Detection System Using an Accelerometer Sensor

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Abstract: Boundary marker displacement is one of the major issues that can lead to unclear territorial boundaries and land disputes. This study aims to design and implement a microcontroller-based boundary marker displacement detection system using an MPU6050 accelerometer sensor to monitor changes in marker inclination in real time. The proposed system consists of an Arduino Uno, an MPU6050 sensor, an I2C LCD, a buzzer, and a battery power supply. Acceleration data along the X, Y, and Z-axes are processed to calculate the roll and pitch angles, which are then compared with a predefined threshold of 20° to classify the marker condition as either Safe or Danger. Sensor calibration was performed with the marker in an upright position as the initial reference before testing. Experimental evaluations were conducted at inclination angles of 0°, 5°, 10°, 15°, 20°, 25°, and 30°, with 30 samples collected at each angle. The experimental results demonstrate that the system consistently changes its status to Danger when the measured pitch angle reaches or exceeds the 20° threshold. The repeatability test, performed over ten trials, produced an average detection angle of 21.18°, while the response time test yielded an average response time of 13.57 s. Furthermore, all experiments successfully detected changes in marker inclination without any detection failures. These results indicate that the proposed system provides stable and consistent performance and is capable of delivering reliable real-time early warnings for potential boundary marker displacement.

Keywords: Arduino Uno; MPU6050; boundary marker monitoring; tilt detection; pitch angle; repeatability; response time.

1. Introduction

Boundary markers are essential elements for defining administrative territories, security zones, and other areas requiring clear territorial boundaries. However, in practice, boundary markers are frequently displaced due to natural factors, human activities, or intentional vandalism, resulting in undetected changes in their positions. Such conditions may lead to boundary ambiguity, land disputes, and security issues in the monitored area. Therefore, an effective monitoring system capable of detecting changes in the position or inclination of boundary markers accurately and in real time is required to support reliable territorial monitoring and early warning mechanisms [1], [2].

Recent advances in sensor and microcontroller technologies have enabled the development of monitoring systems with relatively low implementation costs while maintaining satisfactory measurement performance. Among various sensing technologies, accelerometer sensors have been widely employed for motion and position monitoring because they can measure acceleration, vibration, and object inclination in real time [3], [4]. In this study, the MPU6050 accelerometer sensor was selected due to its capability to provide three-axis acceleration data, which can be processed to calculate roll and pitch angles for detecting changes in the position of boundary markers in real time.

Several previous studies have demonstrated the effectiveness of MEMS-based accelerometer sensors for deformation, displacement, and position monitoring in structural and environmental applications. MEMS accelerometer-based deformation monitoring systems have shown satisfactory measurement precision with relatively low implementation costs [5]. Likewise, displacement monitoring studies have reported that accelerometer sensors can accurately detect position changes in structural health monitoring systems [6]. Furthermore, the MPU6050 sensor has been implemented in microcontroller-based landslide monitoring and inclinometer systems to measure object inclination and movement [7]. Nevertheless, these studies mainly focus on structures, slopes, and infrastructure monitoring. They do not specifically address boundary marker displacement detection systems capable of calculating roll and pitch angles while classifying boundary marker conditions into Safe and Danger states in real time.

Based on this review, a research gap exists in the absence of a dedicated accelerometer-based monitoring system specifically designed for boundary marker displacement detection that integrates roll and pitch estimation with real-time condition classification. Such a system is expected to improve the reliability of boundary monitoring by providing immediate warnings when abnormal marker inclination is detected

The novelty of this research lies in the development of a microcontroller-based boundary marker displacement detection system utilizing the MPU6050 accelerometer sensor to process three-axis acceleration data into roll and pitch angles for real-time position monitoring. The proposed system classifies the boundary marker condition into Safe and Danger categories based on a predetermined threshold angle. The monitoring results are displayed on a 16×2 LCD, while an audible warning is generated through a buzzer whenever the measured inclination exceeds the specified threshold.

Therefore, this study aims to design and implement a microcontroller-based boundary marker displacement detection system using an MPU6050 accelerometer sensor. The proposed system is expected to detect boundary marker inclination and displacement in real time, thereby providing early warning information whenever abnormal movement occurs. Consequently, the system is expected to improve the effectiveness and efficiency of boundary marker monitoring while enhancing security in territorial supervision [8].

2. Materials and Methods

2.1. Materials

2.1.1. Accelerometer Sensor

An accelerometer sensor as shown in Figure 1 is a device used to detect changes in acceleration, tilt, and vibration of an object. In this research, the accelerometer sensor is utilized to detect displacement or position changes of boundary markers in real-time. The sensor operates by measuring acceleration changes along the X, Y, and Z axes, which are then transmitted to the microcontroller for processing. When displacement or tilt changes occur in the boundary marker, the acceleration values detected by the sensor will also change, enabling the system to identify marker displacement. The sensor data are subsequently used as monitoring parameters to determine the condition of the boundary marker more accurately and quickly [9][10].

Figure 1. Accelerometer Sensor

2.1.2. Arduino UNO

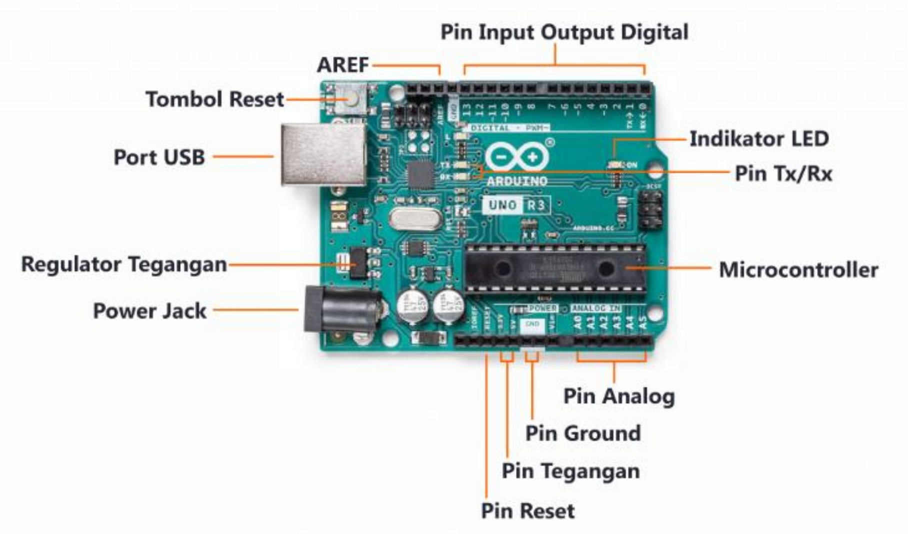


Figure 2. Device Arduino Uno

Arduino Uno as shown in Figure 2 is a microcontroller board based on the ATmega328P that functions as the main controller in the boundary marker displacement detection system. In this research, Arduino Uno is used to receive and process data from the accelerometer sensor, then analyze the data to detect position or tilt changes in the boundary marker. In addition, Arduino Uno controls the monitoring process and data communication within the system. Arduino Uno was selected because it has a simple design, is easy to program, and is compatible with various sensors and electronic modules, making it suitable for developing microcontroller-based monitoring systems [11][12].

2.1.3. LCD 16X2

The LCD 16×2 as shown in Figure 3 is a display device used to present information in the boundary marker displacement detection system. In this research, the LCD 16×2 functions to display accelerometer sensor readings, boundary marker status conditions, and other system information in real-time. The display consists of 16 columns and 2 rows of characters, allowing information to be shown clearly and easily read by users. The LCD 16×2 was selected because it has low power consumption, can be easily interfaced with Arduino Uno, and is widely used in microcontroller-based monitoring systems [13].

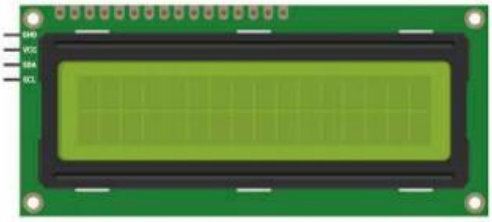


Figure 3. Device LCD 16x2

2.1.4. Buzzer

Figure 4. Buzzer **Device**

A buzzer as shown in Figure 4 is an electronic component used as a sound indicator or alarm in the boundary marker displacement detection system. In this research, the buzzer functions to provide a warning when the accelerometer sensor detects position or tilt changes in the boundary marker that exceed the predetermined threshold. The buzzer produces a sound signal to indicate that displacement has occurred, allowing users to identify the boundary marker condition quickly. The buzzer was selected because it has a fast response, low power consumption, and can be easily integrated with Arduino Uno in a microcontroller-based monitoring system [14].

2.1.5. 18650 Li-Ion Battery

Figure 5. 18650 Li-Ion Battery

This research uses a Lithium-Ion 18650 battery as shown in Figure 5 as the main power source for the boundary marker displacement detection system because it has a relatively large capacity, is rechargeable, and can provide stable voltage to support the operation of the microcontroller and sensors. During operation, the battery supplies electrical energy to electronic components such as the microcontroller, accelerometer sensor, and communication modules, allowing the system to function properly. The movement of lithium ions through the electrolyte and separator from the anode to the cathode generates electrical energy used during the monitoring process. When the battery capacity decreases, it can be recharged through a charging process in which electrons and lithium ions return to their original positions, enabling the battery to be reused as a power source for the monitoring system [15].

2.2. Electronic Schematic Design

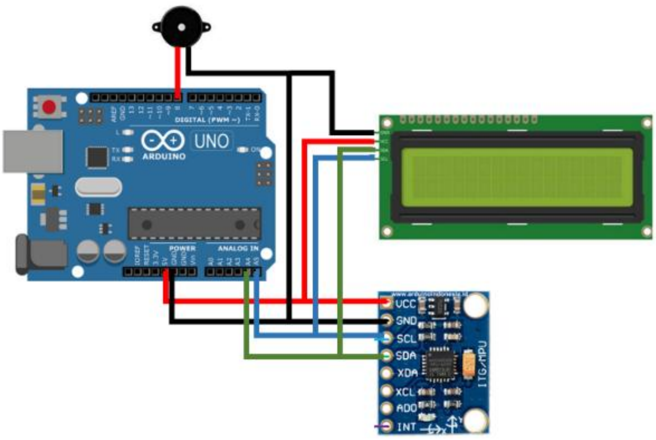


Figure 6. Electronic Schematic Design

Figure 6 shows the schematic design of the boundary marker displacement detection system consisting of an Arduino Uno, MPU6050 accelerometer sensor, 16×2 LCD, and buzzer. Arduino Uno functions as the main controller that receives and processes data from the MPU6050 sensor through I2C communication using the SDA and SCL pins. The MPU6050 sensor is used to detect changes in position or tilt of the boundary marker based on acceleration readings along the X, Y, and Z axes. The sensor readings are then displayed in real-time on the 16×2 LCD, allowing users to monitor the system condition directly. In addition, the buzzer is used as an audible warning indicator when displacement or position changes exceed the predetermined threshold. All components are powered by Arduino Uno, enabling the system to operate in an integrated manner for monitoring boundary marker conditions.

2.3. Boundary Marker Design

The boundary marker system in this research was designed in the form of a prototype equipped with an MPU6050 accelerometer sensor, 16×2 LCD, and buzzer for displacement monitoring as shown in Figure 7, 8, and 9. The accelerometer sensor was placed at the base of the marker to detect position and tilt changes in real-time. The sensor data were then processed by the Arduino Uno microcontroller to determine the condition of the boundary marker.

The 16×2 LCD was used to display system information, including safe status and detected displacement conditions. In addition, the buzzer functioned as a warning alarm when the system detected position changes exceeding the predetermined threshold. The system was designed in a simple form to facilitate implementation as a prototype of an accelerometer-based boundary marker monitoring system.

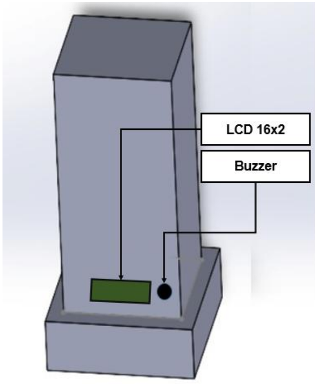


Figure 7. Boundary Marker Design with LCD and Buzzer Placement

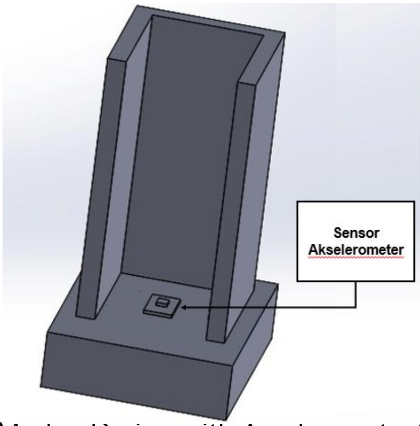


Figure 8. Boundary Marker Design with Accelerometer Sensor Placement

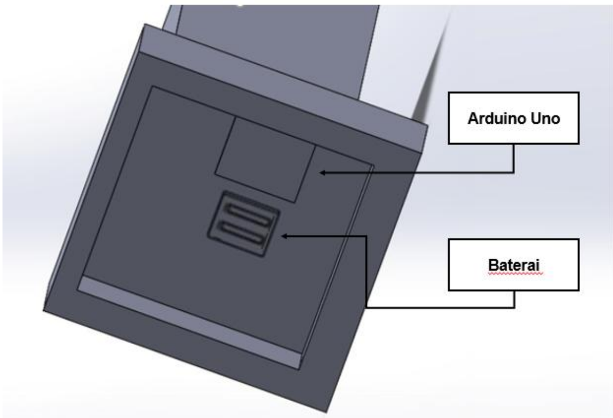


Figure 9. Boundary Marker Design with Arduino Uno and Battery Placement

2.4. System Operation

The proposed boundary marker displacement detection system operates by utilizing the MPU6050 accelerometer sensor to continuously measure acceleration along the X, Y, and Z axes. When the system is powered on, the sensor first performs an initialization process, followed by a calibration procedure while the boundary marker is maintained in an upright position. The initial sensor readings are stored as reference values representing the normal condition of the boundary marker.

After the calibration process is completed, the acceleration data are continuously acquired and processed by the Arduino Uno microcontroller to calculate the roll and pitch angles. These parameters represent the inclination of the boundary marker relative to its initial reference position. The roll and pitch angles are calculated using the following equations.

Equation (1)

$$\boldsymbol{Roll = tan^{-1}\left(\frac{Ay}{\sqrt{Ax^2 + Az^2}}\right) \times \frac{180}{\pi}}$$

Equation (2)

$$\boldsymbol{Pitch = tan^{-1}\left(\frac{-Ax}{\sqrt{Ay^2 + Az^2}}\right) \times \frac{180}{\pi}}$$

where::
Ax = acceleration along the X-axis,
Ay = acceleration along the Y-axis,
Az = cceleration along the Z-axis.

The calculated roll and pitch angles are subsequently compared with a predefined threshold value. In this study, the boundary marker is classified as Safe when both roll and pitch remain within the allowable inclination range. Conversely, if either the roll or pitch angle exceeds the threshold value, the system classifies the marker condition as Danger. Once the Danger condition is detected, the Arduino Uno automatically activates the buzzer as an audible warning and simultaneously displays the roll angle, pitch angle, and system status on the 16×2 LCD in real time. This mechanism enables users to identify boundary marker displacement promptly and take appropriate corrective actions.

Overall, the proposed detection algorithm consists of four main stages: sensor initialization and calibration, acceleration data acquisition, roll and pitch angle calculation, and boundary marker condition classification into Safe or Danger. These stages enable the system to perform continuous real-time monitoring and automatically provide early warnings whenever the detected inclination exceeds the predefined threshold.

2.4.1. Sensor Calibration Procedure

Before the system is used for boundary marker displacement detection, the MPU6050 accelerometer sensor undergoes a calibration procedure to obtain the initial reference values. The calibration is performed by placing the boundary marker in an upright position perpendicular to the ground surface, which is defined as the normal (Safe) condition. Under this condition, the sensor continuously measures acceleration along the X, Y , and Z axes for several seconds to obtain stable readings. The averaged acceleration values are then stored as the initial reference and used as the baseline for subsequent roll and pitch angle calculations.

The purpose of the calibration process is to minimize measurement errors caused by sensor offset and installation variations. By using these reference values, the proposed system is able to provide more stable and consistent inclination measurements during real-time monitoring. The calibration procedure is performed only when the system is initially powered on or whenever the boundary marker is reinstalled, ensuring that the reference values accurately represent the normal operating condition.

2.4.2. Penentuan Nilai Ambang Batas (Threshold)

The threshold value used for boundary marker condition classification was determined through experimental testing using the MPU6050 accelerometer mounted on the boundary marker prototype. The experiment was conducted by gradually tilting the prototype from its initial upright position (0°) to inclination angles exceeding 20°. At each tilt angle, the sensor recorded 30 samples of roll and pitch data with a sampling interval of approximately 500 ms. To ensure the consistency and reliability of the measurements while minimizing the influence of sensor fluctuations, the entire experiment was repeated ten times under the same testing conditions.

The experimental results demonstrated that the proposed system consistently classified the boundary marker as Safe when the measured pitch angle remained below 20°. Conversely, the system changed the status to Danger whenever the pitch angle reached or exceeded 20°. Based on these observations, a threshold value of 20° was selected because it consistently represented the transition point between normal and abnormal boundary marker conditions throughout all experimental trials. Therefore, the threshold adopted in this study was established from experimental measurements on the developed prototype rather than being selected arbitrarily, providing a reliable basis for the system's decision-making process. The boundary marker condition was classified according to the following decision rules:

$$\textbf{Safe,}\quad |Pitch| < 20^0$$
$$\textbf{Danger,}\quad |Pitch| \geq 20^0$$

These decision rules were implemented in the Arduino Uno microcontroller, where each measured pitch value was continuously compared with the predefined threshold. When the pitch angle reached or exceeded 20°, the system automatically activated the buzzer and displayed the Danger status on the 16×2 LCD. Otherwise, the system maintained the Safe status while continuously monitoring the inclination of the boundary marker in real time.

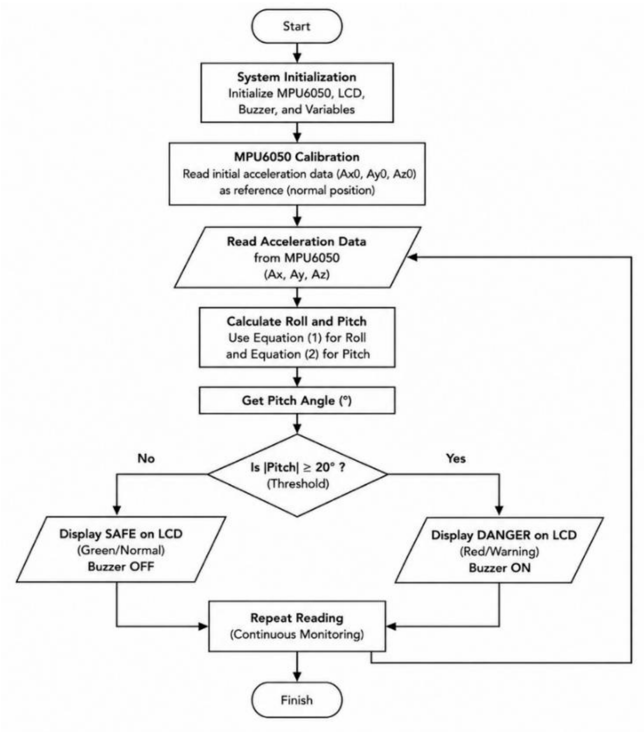


Figure 10. Flowchart System Work

Figure 10 illustrates the overall operating procedure of the proposed boundary marker displacement detection system. The process begins with system initialization, followed by the calibration of the MPU6050 sensor to obtain the reference values under the normal upright position. The sensor then continuously measures acceleration along the X-, Y-, and Z-axes, and the acquired data are processed to calculate the corresponding roll and pitch angles. The calculated pitch angle is subsequently compared with the predefined threshold of 20°. If the pitch angle is less than 20°, the system classifies the boundary marker condition as Safe, displays the status on the 16×2 LCD, and keeps the buzzer inactive. Conversely, when the pitch angle reaches or exceeds 20°, the system changes the status to Danger, activates the buzzer as an audible warning, and displays the warning message on the LCD. This procedure is continuously repeated, enabling real-time monitoring of the boundary marker condition.

3. Results

3.1. MPU6050 Sensor Calibration Results

Before the proposed system was used for boundary marker displacement detection, the MPU6050 sensor was calibrated to obtain the initial reference (baseline) values. The calibration procedure was performed by positioning the boundary marker prototype vertically on a level surface, which was defined as the normal (Safe) condition. Under this condition, the sensor continuously measured acceleration along the X-, Y-, and Z-axes for several seconds. The recorded acceleration data were subsequently used as the initial reference for calculating the roll and pitch angles during the monitoring process.

The calibration results indicate that the measured roll and pitch angles remained relatively stable with only minor variations. Although the measured values were not exactly 0°, this behavior is considered normal for MEMS-based sensors due to inherent sensor noise, bias, and installation tolerances. The reference values obtained during calibration were therefore used as the baseline for subsequent inclination measurements, enabling the proposed system to detect boundary marker displacement more consistently.

Table 1. MPU6050 Sensor Calibration Results

No	Parameter	Value
1.	Average Roll	1,58°
2.	Average Pitch	-8,22°
3.	Status	Safe

Based on the calibration results presented in Table 1, the MPU6050 sensor exhibited stable measurements with only small fluctuations under the normal operating condition. These results indicate that the calibration procedure successfully established reliable baseline values, allowing the proposed system to perform consistent roll and pitch calculations during real-time boundary marker monitoring.

3.2. Threshold Determination Results

The threshold determination experiment was conducted by gradually tilting the boundary marker prototype from its initial upright position to inclination angles exceeding the expected displacement limit. At each test angle, 30 samples of sensor data were collected to obtain the corresponding roll angle, pitch angle, and system classification. The objective of this experiment was to identify the inclination angle at which the proposed system could reliably distinguish between the Safe and Danger conditions.

Table 2. Threshold Determination Results

No.	Test Angle	Average Pitch	Status
1.	0°	-8.2°	Safe
2.	5°	0.3°	Safe
3.	10°	8.5°	Safe
4.	15°	14.9°	Safe
5.	20°	19.6°	Safe
6.	25°	24.1°	Danger
7.	30°	29.0°	Danger

As presented in Table 2, the measured pitch angle increased proportionally with the applied inclination angle of the boundary marker. The proposed system consistently maintained the Safe status while the measured pitch angle remained close to, but below, the predefined threshold of 20°. Once the pitch angle exceeded this threshold, the system automatically changed the classification to Danger in all experimental trials. These results demonstrate that the selected threshold of 20° effectively differentiates normal operating conditions from significant boundary marker displacement. The consistent classification obtained throughout the experiments confirms that the experimentally determined threshold provides a reliable basis for the proposed decision-making algorithm.

3.3. Repeatability Test

A repeatability test was conducted to evaluate the consistency of the proposed system in producing reliable detection results under identical experimental conditions. The experiment was repeated ten times by gradually tilting the boundary marker prototype from its normal upright position until the inclination exceeded the predefined threshold of 20°. During each trial, 30 sensor samples were collected at a sampling interval of approximately 500 ms, resulting in a total of 300 measurements.

Tabel 3. Repeatability Test Results

No	Trial	Detection Angle (°)	Pitch at Detection (°)	Status	Detection Time (s)
1.	1	20	20.99	Danger	12.56
2.	2	20	20.96	Danger	16.59
3.	3	20	20.51	Danger	14.58
4.	4	20	22.59	Danger	11.55
5.	5	20	20.77	Danger	13.06
6.	6	20	20.60	Danger	12.56
7.	7	20	21.74	Danger	13.06
8.	8	20	20.15	Danger	14.07
9.	9	20	23.26	Danger	13.57
10.	10	20	20.22	Danger	14.07

The evaluated parameters included the pitch angle at which the system first classified the boundary marker as Danger, the corresponding detection time, and the resulting system status. The results obtained from the ten experimental trials were subsequently compared to assess the repeatability of the MPU6050 sensor and the consistency of the proposed decision-making algorithm.

The repeatability test results presented in Table 3 show that the proposed system successfully detected the transition from the Safe condition to the Danger condition in all ten experimental trials, resulting in a 100% detection success rate. Although slight variations in the measured pitch angle were observed at the transition point, all recorded values remained close to the predefined threshold. These variations are mainly attributed to the inherent noise characteristics of the MPU6050 sensor and minor differences in the manual tilting process during each experiment.

The recorded detection times also exhibited slight variations because the prototype was tilted manually, causing differences in the time required to reach the threshold angle. Nevertheless, no missed detections or incorrect classifications were observed throughout the experiments. These findings indicate that the proposed system provides stable and repeatable performance for real-time boundary marker displacement detection.

Table 4. Repeatability Test Statistics

No	Parameter	Value
1.	Number of Trials	10
2.	Total Samples	300
3.	Detection Success Rate	100%
4.	Average Pitch at Detection	≈21.18°
5.	Minimum Pitch	20.15°
6.	Maximum Pitch	23.26°

The statistical summary presented in Table 4 further confirms the repeatability of the proposed system. The average pitch angle at the transition point was approximately 21.18°, with measured values ranging from 20.15° to 23.26°. The relatively small variation demonstrates that the experimentally selected threshold of 20° provides consistent detection performance despite minor fluctuations caused by sensor characteristics and manual operation. Overall, these results verify that the proposed system is capable of performing reliable and repeatable boundary marker displacement detection under repeated testing conditions.

3.4. Response Time

A response time evaluation was conducted to determine the time required by the proposed system to detect boundary marker displacement after the measured pitch angle exceeded the predefined threshold. The experiment was performed ten times by gradually tilting the prototype from its normal upright position until the inclination angle surpassed 20°. The detection time was obtained from the timestamp (ms) recorded by the Arduino Uno at the instant when the system classification changed from Safe to Danger as shown in Table 5.

Table 5. Response Time Test Results

No	Trial	First Danger Sample	Time (ms)	Response Time (s)
1	1	21	12557	12.56
2	2	29	16594	16.59
3	3	25	14576	14.58
4	4	19	11547	11.55
5	5	22	13062	13.06
6	6	21	12557	12.56
7	7	22	13062	13.06
8	8	24	14071	14.07
9	9	23	13566	13.57
10	10	24	14071	14.07

The experimental results indicate that the proposed system successfully detected the transition from the Safe condition to the Danger condition in all ten trials. The recorded response time ranged from 11.55 s to 16.59 s, depending on the time required for the manually tilted prototype to reach the threshold angle.

Table 6. Response Time Statistics

No	Parameter	Value
1.	Number of Trials	10
2.	Minimum Response Time	11.55 s
3.	Maximum Response Time	16.59 s
	Average Response Time	**13.56 s**

Based on the test results presented in Table 6, the system was able to detect changes in the boundary marker position with an average response time of 13.56 seconds. The detection time varied from 11.55 seconds to 16.59 seconds. This variation was caused by the manual tilting process of the prototype, resulting in different tilting speeds during each trial. Nevertheless, the system consistently detected changes in condition when the pitch angle reached or exceeded the threshold value of 20°. This indicates that the algorithm implemented on the Arduino Uno microcontroller was able to process the MPU6050 sensor data consistently and provide real-time warnings according to the inclination condition of the boundary marker.

3.5. Repeatability Test

A repeatability test was conducted to evaluate the consistency of the system in detecting boundary marker displacement under the same testing conditions. The experiment was repeated 10 times by gradually tilting the prototype from the normal position until it exceeded the threshold value of 20°. In each trial, 30 data samples were collected with a sampling interval of approximately 500 ms, and the first pitch value at which the system changed its status from Safe to Danger was recorded. The repeatability test results are presented in Table 7 and visualized in Figure 11.

Table 7. Repeatability Test

No	Trial	Pitch at Danger (deg)
1.	1	20,99
2.	2	20,96
3.	3	20,51
4.	4	22,59
5.	5	20,77
6.	6	20,6
7.	7	21,74
8.	8	20,15
9.	9	23,26
10	10	20,22

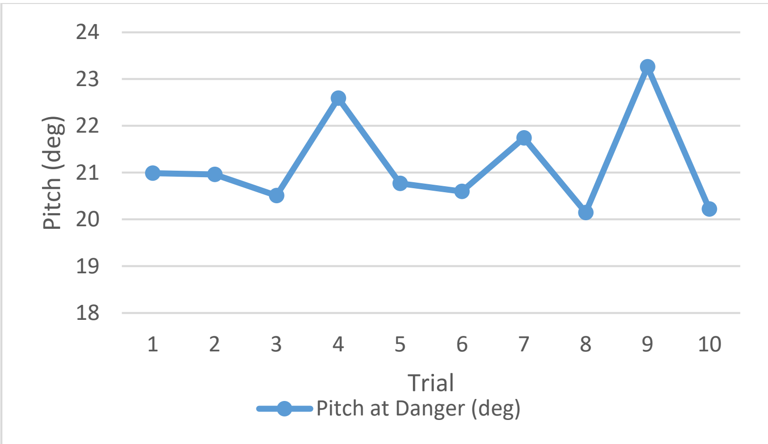


Figure 11. Repeatability Test Graph

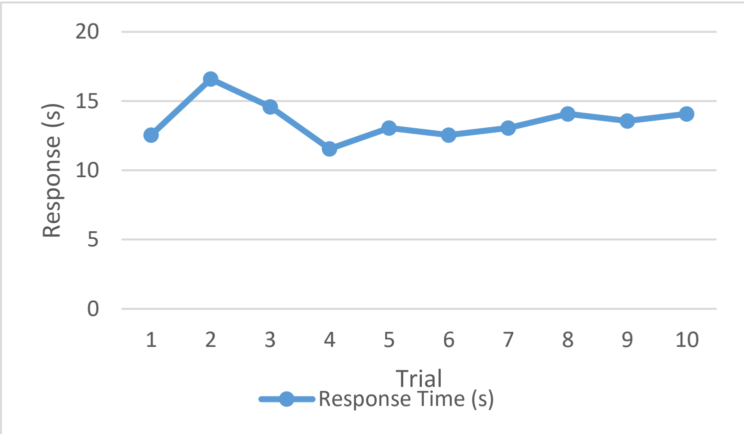
3.6. Response Time Test

A response time test was conducted to determine the time required by the system to detect a change in the boundary marker position after the inclination angle exceeded the threshold value until the system displayed the Danger status. The response time was calculated based on the time difference between the beginning of the test and the moment when the system first detected the Danger condition. The experiment was conducted 10 times using the same procedure as the repeatability test.

Table 8. Response Time Test

No	Trial	Response Time (s)
1.	1	12,56
2.	2	16,59
3.	3	14,58
4.	4	11,55
5.	5	13,06
6.	6	12,56
7.	7	13,06
8.	8	14,07
9.	9	13,57
10	10	14,07

Figure 12. Response Time Test Graph



Based on the results presented in Table 8 and Figure 12, the system achieved an average response time of 13.57 s, with the fastest response time of 11.55 s and the longest response time of 16.59 s. The variation in response time observed in each trial was influenced by differences in the manual tilting speed of the prototype, resulting in different durations required to reach the threshold angle. Nevertheless, all experimental trials demonstrated that the system consistently detected changes in the boundary marker condition without any detection failures. These results indicate that the proposed system provides stable response performance for delivering early warnings of potential boundary marker displacement.

4. Discussion

Based on the experimental results, the MPU6050 accelerometer sensor was able to consistently detect changes in the inclination of the boundary marker by calculating the roll and pitch angles. The sensor data were processed by the Arduino Uno to determine the boundary marker condition based on the predefined threshold value. The results showed that the system maintained the Safe status when the pitch angle was below 20°, while the status changed to Danger when the pitch angle reached or exceeded 20°. This threshold value was established through experimental testing with ten repeated trials, indicating that the classification was not determined arbitrarily but was based on direct measurements obtained from the developed prototype. These findings demonstrate that the selected threshold of 20° effectively distinguishes between the normal condition and boundary marker displacement while minimizing the possibility of false alarms caused by minor inclination changes. The Repeatability Test results demonstrated that the proposed system provided consistent performance, with an average detection angle of 21.18° across ten repeated experiments. The small variations observed between trials were within an acceptable range and were mainly caused by sensor noise and the manual tilting process. In addition, the Response Time Test produced an average response time of 13.57 s, indicating that the system was able to detect changes in the boundary marker condition shortly after the inclination angle exceeded the predefined threshold. These results confirm that the proposed system has good consistency in detecting boundary marker displacement. Overall, the integration of the MPU6050 sensor, Arduino Uno, 16×2 LCD, buzzer, and Lithium-Ion 18650 battery successfully produced a real-time, stable, and reliable boundary marker displacement detection system.

In addition to the detection performance, energy consumption is also an important consideration for practical field implementation. The device uses a Lithium-Ion 18650 rechargeable battery as the power source because it offers relatively high capacity, rechargeability, and wide availability. In this study, the experiments were focused on evaluating the system's capability to detect boundary marker inclination; therefore, quantitative measurements of power consumption, battery operating time, and recharge cycles were not performed. Nevertheless, the use of a rechargeable battery provides greater flexibility for operating the system in locations without a permanent power supply. Consequently, evaluating energy consumption and battery lifetime is recommended as future work to improve the practicality of the proposed system.

The proposed system currently employs a buzzer as a local warning device, meaning that boundary marker displacement can only be detected by users located near the prototype. This approach was intentionally adopted to focus the present study on the development of the inclination detection method using the MPU6050 sensor. To improve its applicability in real-world monitoring, the system can be further enhanced by integrating wireless communication technologies such as LoRa, GSM, Wi-Fi, or the Internet of Things (IoT), enabling real-time transmission of boundary marker status to a remote monitoring center. Such an enhancement would allow remote surveillance and support faster and more efficient responses to potential boundary marker displacement.

5. Conclusions

Based on the results of this study, a microcontroller-based boundary marker displacement detection system using the MPU6050 sensor was successfully designed and implemented. The proposed system is capable of measuring the inclination angle of the boundary marker in real time by calculating the roll and pitch angles and processing the measurement results to determine the marker condition according to the predefined threshold value. Based on the experimental results, a threshold value of 20° was selected because it consistently distinguished between the Safe and Danger conditions.

The Repeatability Test results showed that the proposed system achieved stable performance with an average detection angle of 21.18° over ten experimental trials, while the Response Time Test yielded an average response time of 13.57 s. These results indicate that the system is capable of consistently detecting boundary marker displacement and providing warnings when the inclination angle exceeds the predefined threshold. Therefore, the proposed system has the potential to be applied as an automatic boundary marker monitoring device to support monitoring activities and reduce delays in detecting boundary marker displacement in the field. Future work may focus on quantitatively evaluating energy consumption and battery lifetime, as well as integrating wireless communication technologies such as LoRa, GSM, or the Internet of Things (IoT) to enable real-time transmission of boundary marker displacement information to remote users.

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